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MODULARITY: IMPLICATIONS FOR IMITATION, INNOVATION, AND SUSTAINED ADVANTAGE

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Modular design practices provide a lens on the link among product architecture, imitation, and the dynamic capabilities that sustain long-term performance. Looking at closed product systems, we propose that simplified links between design and performance outcomes in modular environments facilitate imitation. The same reduction in complexity drives development of dynamic capabilities. These take the form of more rapid and reliable search processes for incremental and radical innovations. The scope and timing of a firm's modular strategy influence the development of these capabilities, which are critical to sustainable modular performance advantages.

Modularity is receiving increasing attention as a means of managing complexity and designing flexible organizational and technological systems (Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004; Thomke & Reinertsen, 1998). Interest in modular organizations and products is fueled by the need to understand how firms can better compete in dynamic environments (Eisenhardt & Martin, 2000; Levinthal, 1997; Teece, Pisano, & Shuen, 1997). Continuous technological change, fickle customers, and frequent shifts in the competitive landscape are characteristic of many industries (D'Aveni, 1994), and, regardless of how the degree of turbulence compares with times past (McNamara & Vaaler, 2003), we need to understand how firms succeed in these contexts.

Frequent change challenges two concepts central to strategic management: sustained competitive advantage and distinctive competencies. If markets are perpetually shifting, how can a firm hope to build resources and capabilities that sustain competitive advantage? Moreover, reliable organizational action requires stability in objectives and capabilities (Hannan & Freeman, 1984). If managers cannot discern which activities their firm should commit to and which it should avoid—that is, what kinds of distinctive competencies to build—they will find it difficult to establish appropriate strategic goals for the firm (Andrews, 1971). Scholars are beginning to grapple with these issues, but we are far from offering managers a clear answer.

Barney (1995), for example, argues that durable advantages are attainable in dynamic environments but that, to reveal them, researchers need to examine a firm's position across a series of individual innovations. Eisenhardt (2002), however, maintains that while sustainable competitive advantages may still be possible, managers should not plan for them; in an unpredictable world, counting on anything other than small, ephemeral victories could leave their firm exposed.

The emerging portrait of an effective competitor is an agile firm that responds quickly to unanticipated threats and opportunities. To enable this kind of flexibility, organizational and strategy scholars advocate the use of modular design principles at multiple levels (Levinthal, 1997; Sanchez & Mahoney, 1996). Modular corporate strategies, comprised of loosely coupled simple rules, can be reconfigured as environments shift (Galunic & Eisenhardt, 2001). Modular business unit competencies can be quickly leveraged into other markets as opportunities change (Galunic & Eisenhardt, 2001).

Modularity in product design allows a firm to exploit technological opportunities and to react to evolving market opportunities through recombination, modular innovation, and outsourcing (Thomke & Reinertsen, 1998). Recombination to increase product variety, or to leverage modules

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in new markets, enables a firm to satisfy diverse and fluid customer preferences, and it minimizes the need to predict which product attributes will be most valued (Pil & Holweg, 2004; Sanchez, 1995; Sanderson & Uzumeri, 1995). Through modular innovation, a firm can exploit technological opportunities to improve specific product functions that emerge late in the design cycle (Garud & Kumaraswamy, 1995; Thomke, 1997). And by outsourcing modules, a firm can leverage the design capabilities of loosely coupled networks of suppliers, shifting among them as conditions change (Takeishi & Fujimoto, 2001; Utterback, 1994).

In addition to enhancing fitness in dynamic environments, these adaptive strategies may contribute to a firm's competitive advantage. For example, modular innovation may be used to differentiate a firm's products (Iansiti & Khanna, 1995). By leveraging core modules across several products, a firm can reduce the costs of differentiating through superior module design (Sanchez & Mahoney, 1996). A firm may also outsource noncore modules in order to manage costs and focus on modules that are integral to its competitive advantage (Venkatesan, 1992).

Although the flexibility resulting from modularity may be instrumental in maintaining environmental fitness, it is not clear whether or how modular capabilities contribute to sustainable advantages. Can a firm gain sustainable advantage by adapting more quickly or picking opportunities more effectively than its rivals? Are a firm's modular capabilities or the competencies used to leverage them—its architectural capabilities—a more persistent source of advantage? We investigate these issues in the context of modular product design.

In contrast to previous research on product modularity, we focus on single-product performance advantages in closed systems (Gershenson, Prasad, & Zhang, 2003). Whereas scholars have largely studied the benefits of design modularity for product portfolios, we believe attention to individual products is useful for isolating how modularity affects the persistence of a performance advantage. Moreover, modular principles are used to simplify the design problems associated with delivering specific product functions, and firms invest substantial resources to support innovation at this level (Ulrich & Eppinger, 1999). The durability of functional performance advantages is an important factor in understanding the returns to those investments. We focus on closed product systems because we wish to separate the effects of common interface standards, which define open systems, from functional and physical decoupling, which define product design modularity (Gershenson et al., 2003; Takeishi & Fujimoto, 2001).

In this paper we examine the dilemma firms face regarding modularity. On the one hand, modularity leads to greater imitation, undermining the sustained market performance of a firm. On the other hand, modularity allows for better adaptation to different customer segments and facilitates specific types of innovation. We propose that, under certain conditions, the innovation advantages of modularity substantially outweigh the imitation impact on sustained performance.

We begin by defining modular capability in terms of two elements: (1) the problem-solving processes used to improve the product's design and (2) the resulting performance criteria. The links between product design parameters and performance outcomes are more transparent in modular architectures; this facilitates imitation. We propose that the risks associated with reduced imitation barriers can be offset by (1) the impact of product heterogeneity and associated capabilities, (2) the nature of innovation in a modular design environment, and (3) firm-level decisions that augment the innovation advantages associated with modularity.

With respect to product, we propose that, in closed systems, heterogeneity in firms' product architectures and associated modular capabilities reduces imitation risk. With respect to innovation, we theorize that modularity results in more rapid and reliable incremental performance improvements, and it increases the likelihood of radical component innovation. These enhance durability by enabling a firm to maintain performance advantages vis-à-vis rivals with less modular designs. At the firm level, we suggest that lead time and the scope with which modular functions are applied augment the innovation advantages associated with modular design. We conclude by discussing the implications of our theory for some central themes in the strategy and modularity literature and by offering suggestions for further research.

THE NATURE OF MODULARITY

Modular systems are composed of elements, or "modules," that independently perform distinctive functions (Gershenson et al., 2003; Simon, 1962). Modular elements can evolve autonomously, without altering the overall structure of the system. Consequently, modular systems are often more robust to changes in their environment than systems composed of tightly coupled elements (Levinthal, 1997; Orton & Weick, 1990). This property has attracted the attention of management scholars seeking to understand organizational fitness for dynamic environments (Galunic & Eisenhardt, 2001; Schilling, 2000).

In a product system a module is a component or group of components (i.e., subassemblies or subsystems) designed to deliver a unique function, necessary for the product to operate as desired, and independent of other modules' functions. Independent modules do not exchange information, energy, or material to perform their function, nor do they require spatial coordination (Pimmler & Eppinger, 1994; Sanchez, 1999). Product architecture consists of three elements: a set of functions, a map of functions to modules, and interface specifications that explain how modules relate to one another (Baldwin & Clark, 2000; Ulrich, 1995). For a modular product, the goal is to cluster components according to similar functional impact and to reduce dependencies between components assigned to different clusters (Gershenson et al., 2003). Products exhibit varying degrees of modularity according to what proportion of their components reside in modules and how independent those modules' functions are from one another (Gershenson, Prasad, & Zhang, 2004). The most modular architecture embodies one-to-one mapping between functions and modules (Ulrich, 1995).

Product architectures shape the information filters, problem-solving strategies, communication channels, and coordinating routines that make up a firm's capabilities for innovation (Henderson & Clark, 1990; Sanchez & Mahoney, 1996). Each of these affects a firm's ability to search for new solutions to design problems in order to influence product performance. Modular architectures facilitate search by reducing three facets of design complexity associated with managing specific product functions: size of the design problem, interdependence among its elements, and sensitivity of functional requirements and performance to changes in design parameters (El-Haik & Yang, 1999). These problem-solving advantages are gained within modules and form a key element of a firm's modular capabilities.

Exceptional performance on modular performance criteria is achieved through superior module design. For example, Sanderson and Uzumeri (1995) describe how a performance criterion—stable tape speed—in tape players was directly controlled by Sony via a servo system, rather than earlier systems involving a series of interactions including a flywheel connected via a belt to the motor. A firm must protect its module design from imitation to sustain its modular performance advantages and/or to improve it faster than other firms. We compare the persistence of advantages on performance criteria that are implemented by varying degrees of modularity to suggest how modularity affects the dynamics of imitation and innovation.

Firms use varying levels of modularity to manage a particular function, for several reasons. One of these is that they rely on modular design principles to support different goals. For instance, a major objective of using modular design in software has been to facilitate updating product functions in order to rapidly respond to evolving user needs and to facilitate reuse (Fichman & Kemerer, 1993). In the aircraft sector, modular design provides a means of involving lead users in product design (Sanchez & Mahoney, 1996). Modular principles have also diffused more widely in industries such as personal computing and bicycles, where competition focuses on increasing product variety and lowering costs (Takeishi & Fujimoto, 2001; Utterback, 1994). Baldwin and Clark suggest that modularity is easier and more likely for products based on electricity than for mechanical systems because of the unidimensional flow of electrons (1997a). The one-dimensional nature of electricity flow contrasts with multidimensional surfaces that must be coordinated for mechanical systems, such as cars and airplanes, and that therefore require more complex interfaces.

Even across competing firms, heterogeneity may exist in how modular design practices are used. In some firms the degree and approach to modularity may still be an emergent property of product development efforts, rather than an objective, guiding, systematic, upfront design (Ulrich, 1995). Competitors within an industry may seek competitive advantage in different product dimensions and, hence, choose to modularize different functions. For example, in the notebook computer industry, some firms can choose to emphasize display resolution—a change that can be managed relatively easily because it involves modular design changes—whereas others can focus on display size—a design change that is harder to manage in a modular fashion (Hoetker, 2006).

Finally, even if firms emphasize the same product function, they may modularize its design to varying degrees. Although modularity has been an important concept in the product design literature for some time (cf. Alexander, 1964; Parnas, 1972; Suh, 1984), the "science" behind these principles, which would, for example, provide guidance as to how much modularity is optimal and how best to achieve it, is only beginning to develop (Ethiraj & Levinthal, 2004). There are many approaches and little consensus on the ideal techniques for implementing modular design principles (Gershenson et al., 2004).

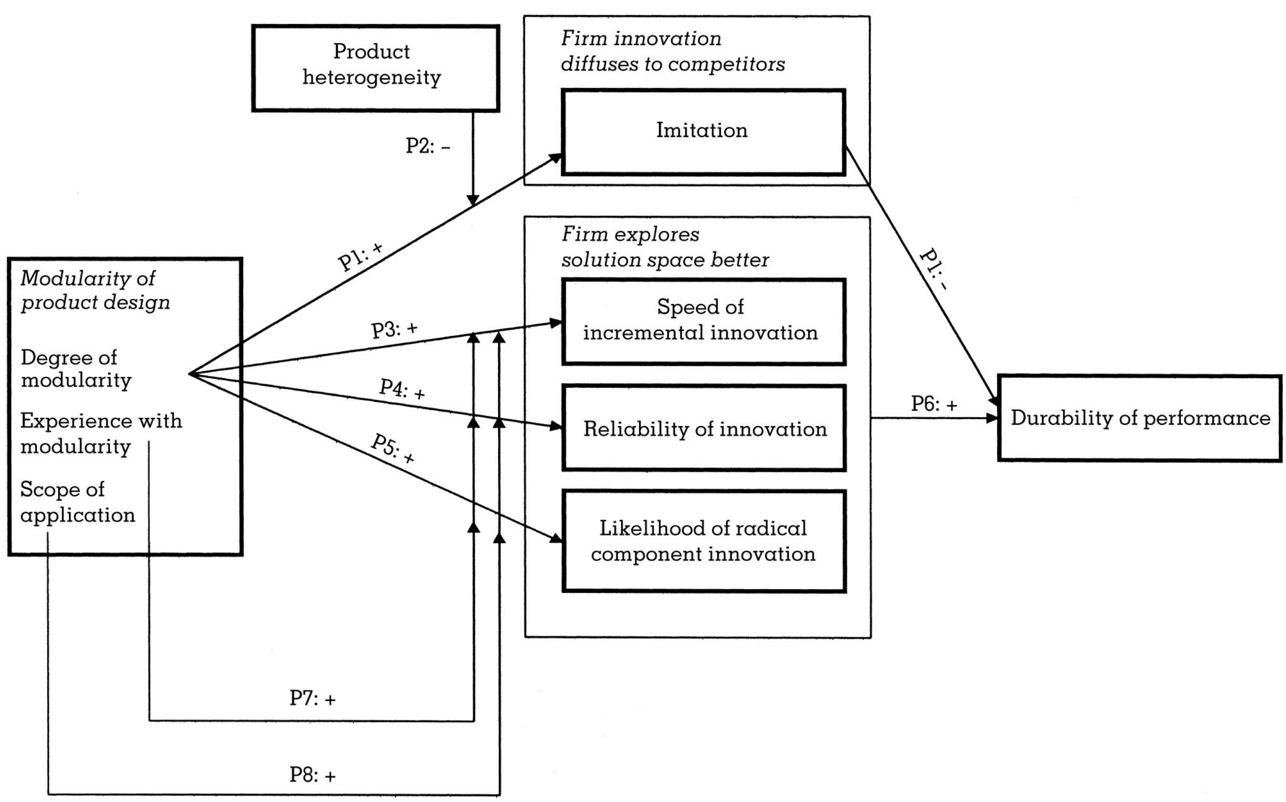
MODULAR DESIGN AND DURABILITY OF PERFORMANCE ADVANTAGE

Modularity, through both imitation and innovation, can have important implications for performance. In this section we develop propositions on how the use of modular design principles and certain product and firm differences may affect the durability of product performance advantages. The propositions we develop are diagrammed in Figure 1.

Modularity and Imitation

Superior product performance has an important influence on firm outcomes in many industries, but such product performance advantages are often difficult to sustain (Mansfield, Schwartz, & Wagner, 1981). Competitors typically have information about their rivals' product development efforts within six to eighteen

FIGURE 1
Modularity of Product Design and Durability of Performance—Key Propositions



months, and patents are ineffective in most industries (Levin et al., 1987). Changes in patent law have resulted in more rapid release of patent application information (Graham & Mowery, 2003), and firms may use the information thus released by their competitors as part of the patenting process, to inform their own search for solutions and to find ways to invent around patents (Cohen, 1995).

Although imitation of new and improved products cannot be prevented, it can be delayed or made difficult through various strategic interventions (McGaughey, 2002). From a design perspective, more complex designs take longer to understand and imitate for a number of reasons (Lippman & Rumelt, 1982; Winter, 1987). The structural complexity embedded in a product may hinder reverse engineering. In particular, products that embody many dependencies between components and rely on multiple components and subsystems to implement a given function will take longer to decipher. The mapping of functions to components cannot be directly observed, and one approach is to glean these through experimentation with a product. The more relationships exist between each product function and the components or subsystems that make up the product, the greater the number of experiments required to reveal them (Rivkin, 2000).

Knowledge diffuses between companies through informal conversation among peers, suppliers, and customers, as well as via employee turnover (Appleyard, 1996). Diffusion is slower when performance knowledge is fragmented in organizations, such as those developing complex products. Functional requirements are mapped to multiple subsystems and components, and, as a consequence, many different types of technological expertise may influence each function. At the organizational level, complex knowledge tends to be more tacit, since each designer is able to explain less about how a product performs (Nelson & Winter, 1982). Moreover, integral designs require more design coordination, and resulting performance criteria are based on knowledge that is socially and procedurally complex. As a result, competitive intelligence is unlikely to generate complete knowledge of how complex products attain performance advantages.

The liabilities of incomplete knowledge are compounded by the fact that interdependence in a design makes its performance more vulnerable to small variations (Rivkin, 2000). Interdependence among multiple elements that affect a given performance dimension means that the performance landscape for that dimension has many local optima, making imitation more difficult (Fleming & Sorenson, 2001; Kauffman, 1993). Since there may be little correlation between the similarity of designs and their performance, firms will find it extremely difficult to learn incrementally from each other. At the same time, more information is required to describe the design and functioning of a complex product, and, because this information is harder to obtain, it is more likely to be incomplete (Sorenson, Rivkin, & Fleming, 2003). Hence, the odds of exactly replicating the performance of a design decline with its complexity.

Reverse engineering, competitive intelligence, and partial design imitation should each be more effective when the relationships between product architecture and performance outcomes are simpler (Baldwin & Clark, 2000; McEvily & Chakravarthy, 2002; Ulrich & Tung, 1991). The enhanced transparency between the inputs and outputs in the functional structure with modular designs means that rivals do not need to understand as much of a firm's design or design process to copy it or to learn from it in order to enhance their own product performance (El-Haik & Yang, 1999). If the modular performance criteria are valuable to customers, competitors have an incentive to replicate them, and because imitation is easier, the performance advantages derived from modular product designs are less durable. These arguments suggest the following.

> *Proposition 1: Modularity will be positively related to the speed of product design imitation and, hence, negatively related to the durability of product performance advantages.*

Although modularity is associated with a simpler, more transparent architecture, implementing modular principles is not easy. As discussed earlier, a product's architecture consists of a set of functions, a map linking functions to the modules that implement them, and interface specifications that determine how the modules come together as an integrated whole. Techniques exist to assist managers and engineers in making these choices, but none is sufficient to predict what an optimal modular architecture would look like (Ethiraj & Levinthal, 2004). Creative and analytical tools, such as analogies and product matrices to plot various relationships, can help to conceptualize alternative functional decompositions and their implementation (Gershenson et. al., 2004; Nonaka & Takeuchi, 1995). These tools guide a firm's efforts to learn about its architectural choices by structuring its knowledge of relevant technologies and performance outcomes. However, a great deal of experimentation and trial and error are still likely to precede acceptance of a modular architecture (Baldwin & Clark, 2000).

Product design always involves uncertainty, but modular design is especially difficult because a firm is locked into its architectural choices for a substantial period of time (Ulrich, 1995). Decisions that delimit the boundaries of product modules and define their interfaces cannot be continuously updated as a firm learns more about their performance, yet the costs of poorly specifying the architecture can be high (Ethiraj & Levinthal, 2004). To manage uncertainty and the potential costs, firms are encouraged to apply modular design principles to products they understand relatively well (Baldwin & Clark, 2000). Although the basic concepts that shape the design of such products may be common knowledge,[1] the design of lower-level components can change radically in their composition and functional responsibilities and can differ greatly across firms (Christensen, Suarez, & Utterback, 1998; Iansiti & Khanna, 1995).

To allow for innovation, a product's architecture needs to embody flexible interface specifications. In modular products, interfaces are specified as a range of values that certain design parameters can take on—for example, physical dimensions and tolerances of the module—without disrupting the performance of other modules. The range selected delimits a firm's opportunities to engage in component innovation and affects the performance of individual modules (Thomke & Reinertsen, 1998). Variation in functional mapping also generates heterogeneity in the modularity of certain performance criteria and, hence, the fluidity of the underlying designs. Architectural choices can lock a firm into tradeoffs among performance criteria by limiting its ability to exploit certain kinds of technological opportunities while favoring others.

Experience shapes engineers' knowledge of the performance potential embodied in alternative technologies and their expectations for how technologies will evolve (Henderson, 1995). This knowledge, in conjunction with a firm's idiosyncratic performance goals, influences the architectural choices, functional mapping, and interface specifications a firm makes. Architectural variation will therefore be greater among products comprising many technologies, in which competitors possess heterogeneous competence (Brusoni & Prencipe, 2001; Pavitt, 1998). If customers also value functions differently, competitors may have unique approaches to the performance criteria they maximize via their architectural choices.

The automobile industry is characterized by diverse technologies and customers. For example, firms can select between two fundamentally different technological approaches for door cassette subsystems (also known as "door inners" or "door plugs"), with different implications for the customer. The first is based on a pressed metal carrier; this carrier enhances ease of repair and provides good water sealing properties and good side-impact crash protection. The second is based on a molded plastic carrier; the plastic provides better integration opportunities, reducing module assembly time, weight, and, in the longer term, cost. However, the plastic carrier–based door cassettes do not provide the same degree of rigidity and crash protection. The fact that there are technological tradeoffs and diverse customer preferences means there is no best choice. Consequently, firms choose unique sets of tradeoffs, appeal to different customer groups, and develop distinctive competencies according to the particular combination of technology and performance criteria they emphasize.

[1] Established products, for example, acquire a "normal configuration"—that is, agreement about the broad functions in a product and which subsystems implement them (Vincenti, 1990). For example, in an automobile the engine is responsible for propulsion, while the body protects passengers from weather. "Operational principles" may also be common knowledge; this is a general understanding of how a device achieves its special purpose or how to affect its performance (Vincenti, 1990). Examples include (1) increasing the number of integrated circuits on a semiconductor to raise processing speed and (2) inhibiting renin secretion to reduce blood pressure.

Direct imitation is not possible when a firm's product embodies a different functional mapping and/or set of interface specifications. Further, since these parameters constrain and channel performance improvement efforts, competitors will find it harder to develop substitute solutions for the criteria a firm excels in. If competitors have committed resources to support different customer needs, they may be unwilling to make the same performance tradeoffs inherent in a firm's design strategy. Since modular architectures are frozen over several design cycles and there are increasing returns to exploitation, modularity may magnify initial differences in firms' capabilities (March, 1991; Schilling, 2000). Further, when competitors follow distinctive technical approaches, they may lack the absorptive capacity to rapidly adopt an innovation in a different technical domain, even if modularity facilitates its identification (Cohen & Levinthal, 1990; Lane & Lubatkin, 1998).

Variation in how firms modularize a product criterion thus arises from uncertainty in at least three areas: (1) how to decompose a product into functions, (2) how best to implement those functions, and (3) how to integrate them. Uncertainty leads to choice based on heterogeneous experience and idiosyncratic expectations, which lock firms into unique architectures for substantial time periods. Heterogeneity in modular architectures will limit firms' abilities to replicate each other's modular solutions.

Proposition 2: Product heterogeneity negatively moderates the relationship between modularity and imitation.

Modularity and Innovation

The best antidote to performance erosion through imitation may be to search the solution space faster than competitors (Kogut & Zander, 1992). Modularity can accelerate search within a problem domain, enabling a firm to devise successively better solutions, by (1) simplifying the conceptual domain of the solution space, (2) maintaining stability in the boundaries of the solution space over time, and (3) decoupling the solution space from other elements of the product system. These structural characteristics of modular design processes enable firms to solve problems faster, more reliably, and using more radical solutions, respectively.

Modularity and speed. In simplifying product design, modularity reduces the information-processing burden associated with performance improvement, enhancing the speed with which firms can search the solution space. The solution space for modular criteria is made conceptually simpler in three ways. First, the target design involves fewer dependencies between components and subsystems and, as a result, entails significantly less complexity. This reduces the number of design alternatives that developers must consider in order to select the best means of improving performance. With fewer functions mapped to each component or subsystem, the number and diversity of performance criteria decrease and the task of evaluating alternative solutions is simplified.

A second factor that facilitates finding superior solutions in a modular environment is that modular components tend to be clustered according to technological similarities, such as reliance on common materials or scientific principles (Gershenson et al., 2003). This enables more shared knowledge for those designing the subsystem, accelerating joint problem solving. Since each component or subsystem maintains a consistent functional focus, developers may acquire cumulative experience with certain kinds of problems faster. This enables them to search for and evaluate alternative solutions more quickly.

A third factor enhancing the speed with which designers evaluate the solution space is that modular product development generally entails hierarchical decoupling (Sanchez & Mahoney, 1996). Engineers can work more closely with others in their unit, and development activities are less likely to be delayed because of conflicts between groups with different performance priorities (Ulrich & Tung, 1991). As a result of the factors simplifying the solution space for superior modular criteria, we expect the following.

Proposition 3: Modularity will be positively related to the speed of incremental product performance improvement.

Modularity and reliability. The design interface parameters that sustain modular design practices are established for several generations or for the life of the product. This has an important advantage for problem solving: it constrains the solution space and allows for more cumulative learning. More of what developers learn with each design cycle can form the foundation for subsequent improvements, because key parameters of the solution space remain unchanged.

In contrast, when design strategies are not modular and there are interdependent effects on performance outcomes, a small change in design can have dramatic and unpredictable consequences for performance. This reduces the value of a firm's prior experience in making further design changes (Ethiraj & Levinthal, 2004; Fleming & Sorenson, 2001; Levinthal, 1997). Knowledge of interdependent outcomes accumulates slowly, and small changes in design parameters can suddenly make a firm's extant understanding obsolete. Further, in interdependent systems, changes made by one development group alter the parameters others have to work within. Each group must constantly adapt to constraints that are imposed by other groups' actions (Levinthal & Warglien, 1999).

Modular design approaches result in more stable, predictable outcomes (Levinthal & Warglien, 1999; Orton & Weick, 1990). The physical decoupling of components and subsystems improves the predictability of design changes. Engineers may also be more certain of what they learn, because the outcomes of their design changes are not affected by parameters under the control or influence of other development teams—that is, by changes made to satisfy other functional requirements.

> *Proposition 4: Modularity will be positively related to the reliability of incremental product performance improvement.*

Modularity and radical innovation. Modularity permits decoupling intramodule design decisions and changes from the rest of the product, promoting greater flexibility in how firms achieve performance objectives (Brown & Eisenhardt, 1998; Sanchez, 1995). This flexibility manifests itself not just in how changes are made to the functional parameters embodied in a component but also in how modules are integrated and combined. In particular, the overall performance of modular systems is more robust, because changes in any one part of the system are less likely to affect other parts of the system (Orton & Weick, 1990).

As a result, decoupling reduces the risks and coordination costs associated with experimentation and permits continuous innovation, including radical technological change, at the component level (Garud & Kumaraswamy, 1995; Sanchez, 1995). Firms can incorporate components that exploit novel technology at a lower cost, since the effects of change are localized (Garud, 1997; Sanchez & Mahoney, 1996).

Component or subassembly teams work autonomously to improve distinct functional requirements. As long as the interface parameters do not change, development teams can experiment with and dramatically alter their own module design strategies without requiring modifications to other components or subassemblies (Fichman & Kemerer, 1993; Ulrich, 1995). The upfront specification of interfaces between modules results in embedded coordination—coordination that is achieved through product design parameters, rather than through formal reporting relationships or direct communication (Sanchez & Mahoney, 1996). Information required for cross-module coordination is visible to all, but intramodule design decisions are hidden (Baldwin & Clark, 2000). Consequently, we expect the following.

> *Proposition 5: Modularity will be positively related to the likelihood of radical innovation at the component and subsystem level.*

Superior search and sustainable advantage. The preceding propositions explain the kinds of innovation advantages a firm may gain through modular product design. We next relate those benefits to the durability of modular performance advantages. In order to build these links, we use the concept of a landscape or topography of solutions to the search for superior modular performance (e.g., Fleming & Sorenson, 2001; Kauffman, 1993; Levinthal, 1997; Rivkin, 2000). A landscape offers a visual depiction of the solution space that a firm and its competitors must search in order to develop superior product designs. The degree of interdependence between design choices that affect a given functional performance outcome determines the ruggedness of the landscape (i.e., the effect that a particular choice has on performance depends on how a number of other decisions are made). The greater the interdependence, the more rugged the landscape, in the sense that it is populated by a larger number of functional performance peaks of varying heights.

We assume that competitors begin searching this topography at the same time. While initial design decisions are informed by prior experience, firms do not know the "true" shape of the entire landscape, so their starting points are subject to some degree of chance. There are three main differences in potential starting positions, with respect to the performance of the firms' designs: (1) a firm begins on a peak with a different initial performance level than its competitors, (2) a firm begins on a peak that offers a different rate of ascent or rate of performance improvement than that of its competitors, (3) a firm begins on a peak with a different summit or possible maximum level of performance than its competitors.

Our starting point is to focus on a firm that has gained a functional performance advantage, so by design and good fortune it starts at a higher initial level of performance. We propose how modularity affects the firm's ability to sustain that relative position through innovation. Given our arguments for Proposition 3, the firm should be able to more quickly scale the peak representing its initial component/subsystem design than its competitors with less modular designs by making incremental changes to that design. Proposition 4 suggests that a firm searching a landscape defined by more modular design will also be able to jump to a higher performance peak more reliably, as a result of changes at the component or subassembly level, because the outcomes from those changes will be more predictable. Our reasoning for Proposition 5 indicates that a firm can more easily reconfigure the entire landscape by making radical innovations at the component level or by fundamentally altering a component choice (e.g., replacing a CD unit with a combined CD/DVD unit in a computer). Each of these innovation advantages suggests that enhanced search under modularity has positive implications for sustainable modular performance advantages:

> *Proposition 6: The innovation advantages gained through modular design will be positively related to the durability of a firm's modular performance advantages.*

CONTINGENCIES

Experience

Firms adopt modular design principles at different times, and first movers may gain experience advantages that are difficult to overcome. However, late adopters may avoid some of the trial and error required to debug the product design process and move down the learning curve associated with specific performance criteria (Argote, 1999; Ethiraj & Levinthal, 2004). In the context of modular product design, for example, competitors may reverse engineer a firm's products to discern how the firm allocated functions to components and how the components were designed in order to affect specific performance criteria (Ulrich & Tung, 1991). A rival might choose to replicate (some of) these choices rather than experiment with alternative designs, particularly if the focal firm has attained superior product performance. Late movers may thereby achieve a higher initial level of product performance compared to that attained by early adopters (Argote, 1999). Since considerable upfront effort is required to design products according to the principles of modularity, the savings in time and effort could be substantial (Baldwin & Clark, 2000).

Imitation is rarely perfect, however, and replicating a firm's product design may be insufficient to overcome the advantages associated with being among the first to adopt modular design principles. Late movers lack the stocks of technological knowledge that early movers accumulate, as well as their organizational experience; these are subject to asset mass efficiencies and time compression diseconomies, which may sustain early mover advantages (Dierickx & Cool, 1989; Pil & MacDuffie, 1996).

Asset mass efficiencies refer to the dynamic whereby accumulating a critical mass of experience makes it easier to acquire more knowledge in related domains (Cohen & Levinthal, 1990; Dierickx & Cool, 1989). Learning is characterized by asset mass efficiencies because it is an associative process; new experiences that can be mapped onto preexisting categories are easier to comprehend and use (Bower & Hilgard, 1981). Engineers, for example, come to understand a product in terms of its architecture and components. As a result, they tend to organize stocks of technical solutions and heuristics for manipulating certain functions and performance criteria according to the structure of the products and components they have worked with (Laudan, 1984; Vincenti, 1990). Through experience, developers become increasingly proficient at solving problems using the conceptual domain and set of technical constraints defined by a specific approach to designing a product's architecture.

Experience with particular modular product architectures enhances problem solving in several ways. Engineers can recombine elements of prior solutions and rely on analogical reasoning to generate new design alternatives, accelerating the rate at which incremental performance improvements are made (Clark, 1985; Usher, 1954). They can better select among design alternatives, because they understand how the constraints embodied in the product architecture affect certain technological approaches; this increases the reliability of a firm's performance improvement across design cycles (Fleming & Sorenson, 2001).

Experience with modular design also facilitates radical innovation. Firms accumulate broad, system-level knowledge in the process of designing modular architectures, and this facilitates the absorption of scientific and technological discoveries and may enable radical component innovation[2] (Baldwin & Clark, 2000; Cohen & Levinthal, 1990; Ethiraj & Levinthal, 2004; Iansiti & Clark, 1994). In addition, much of the knowledge underlying effective decision making becomes tacit with experience, in the sense that individuals no longer consciously attend to it (Nelson & Winter, 1982; Polanyi, 1996). This frees cognitive resources and creates slack in the development process, enabling a firm to solve more taxing problems, such as those that require the generation or exploitation of new knowledge.

Finally, technology and organizational structures must be aligned in order to enable effective and efficient collective outcomes (Jelinek, 1977). Indeed, studies suggest that firms may need to substantially modify their development practices to accommodate modular design (Baldwin & Clark, 1997b). Since there is no widely accepted method for designing modular architectures, part of the initial learning process involves discovering how best to adjust development practices in order to undertake and sustain these design efforts (Sanchez, 1995; Sanchez & Mahoney, 1996). Lead time in utilizing modular design principles enables a firm to identify how its organization needs to change, as well as to develop and gain proficiency in both the formal and informal processes associated with modular design (Brusoni & Prencipe, 2001; O'Sullivan, 2001).

Organizational capabilities are crucial in helping a firm to exploit emerging development opportunities and to commercialize new products ahead of others. Moreover, organizational change is susceptible to time compression diseconomies; efforts to accelerate learning (e.g., by modifying too many activities at once) are likely to produce mistakes and a lesser depth of understanding (Dierickx & Cool, 1989). Hence, early mover advantages will be difficult to overcome. Based on these observations, we propose the following.

> *Proposition 7: Experience using modular design principles positively moderates the relationship between modularity and innovation.*

Scope

Firms can apply modular design principles across several products, and in much of the literature scholars have examined the benefits of leveraging modular components for cost advantages and product variety. To enable these benefits, a firm standardizes interface parameters for modular components and subsystems across products or product families (Jiao & Tseng, 2000; Kogut & Kulatilaka, 1994; Meyer, Tertzakian, & Utterback, 1997). Meyer and Lehnerd (1997), for example, show how the modularization of Black and Decker's basic motor platform made it possible for the company to enhance its complete line of power tools. Sanderson and Uzumeri (1995) similarly describe how Sony leveraged modular components, such as a superflat motor and "chewing gum battery" (a rechargeable NiCd battery), to generate almost 250 variations of its Walkman in the 1980s. This enabled it to

[2] For example, a theory relating chemical composition to the conductivity of certain kinds of metals may create opportunities to redesign a particular set of components. Broad knowledge of how the functionality embodied in those components is affected by fixed interface parameters can help a firm assess whether and how it can exploit the performance potential of a new material.

service market niches at low cost—niches that many of its competitors like Panasonic, Toshiba, and Aiwa could not adequately target.

The scope of application on which such product elements are utilized determines how quickly a firm acquires experience with modular design, as well as the diversity of knowledge it accumulates about modular performance criteria (Ulrich, 1995). Barriers to performance improvement often reside in the application environment—for instance, in ambient conditions or the way a product is used with other technologies or procedures—making knowledge of the application context critical for improving product functionality (Rosenberg, 1982). Leveraging a functional element on a broader scope expands the range of learning opportunities with respect to design alternatives and their performance potential. At the same time, a firm acquires deeper knowledge of the technologies used to deliver that function.

This combination of technological specialization and application breadth has been associated with continuous performance improvement (Iansiti, 1997). The more products embody a particular function and a common approach to delivering it, the faster a firm will accumulate knowledge about barriers to functional performance and how to overcome them. Subjecting a component to a broad range of contexts also increases the adaptability or transferability of a firm's design knowledge and, hence, its ability to improve performance with each development cycle, even when technologies and customer preferences change (Argote, 1999; Bower & Hilgard, 1981). By exposing product development processes to a broader range of contingencies, a firm will likely make the design processes themselves more reliable.

Scope may also increase a firm's proficiency with radical component innovation, enabling it to periodically gain larger performance improvements and to increase the gap between its products and those of competitors. In this way, scope is also related to product heterogeneity, as discussed earlier. Radical component innovation is costly and produces less predictable performance advantages than do incremental changes to design (Christensen, 1992; Iansiti & Khanna 1995). A firm that uses a modular function on a broader scope may be able to exploit the knowledge accumulated through radical component innovation in a more flexible manner, reducing the risks of undertaking these projects. For example, a platform component or subsystem can be shifted to products serving different market segments over time so as to effectively defray the costs of radical R&D. AT Cross and Pentel leverage key modules from one market niche to the next, and EMC Corp utilizes modularity to offer step-up functionality of its mainframe storage product to customers.

Moreover, broad functional experience may be helpful in informing radical innovation initiatives and increasing the odds of improved performance. Diverse application knowledge is instrumental in resolving performance tradeoffs in design, and although modular functions are designed within the constraints of standard interface parameters, the process of developing platform specifications generates broad technological knowledge that may also increase the efficacy of radical component innovation.

Proposition 8: A firm's scope in deploying modular design principles will positively moderate the relationship between modularity and innovation.

CONTRIBUTIONS AND FUTURE RESEARCH

We proposed that modularity may facilitate imitation with negative consequences for the durability of modular performance advantages (see Figure 1 for a summary of our propositions). However, firms modularize their products in unique ways, especially when customer preferences and technologies are complex. The resulting heterogeneity in modular capabilities limits imitation and may enable firms to "capture" distinct customer segments by offering consistently better performance on specific functional criteria. We further argued that superior modular performance can endure, because firms modularize their products to varying degrees and greater modularity provides innovation advantages that can sustain superior performance. We proposed that these advantages are augmented by experience with modular design and the scope of a firm's modular capabilities.

Our arguments are consistent with some research on modular capabilities. Eisenhardt and Martin (2000) suggest that dynamic capabilities, which are similar to architectural capabilities but reside at the corporate level, are relatively homogeneous across firms and that durable advantages reside in the resources (modules) they are used to combine. Roy, McEvily, and Sorenson (2004) have found evidence that modular capabilities enable firms in the machine tool industry to develop superior product innovations and survive radical technological change.

Other authors have suggested that architectural capabilities provide more enduring advantages (Christensen, 1992; Henderson, 1992). Since they span technological boundaries and, potentially, also organizational boundaries, these capabilities tend to be more idiosyncratic and difficult to copy (Takeishi, 2002). Moreover, there is evidence that interdependence among the decisions that make up a firm's competitive strategy (Rivkin, 2000), practices that underlie a capability (Pil & MacDuffie, 1996), and the assets, resources, and capabilities that support a firm's distinctive competence (Thompke & Kuemmerele, 2002) does prevent imitation.

Future research could begin to resolve these views by clarifying how their level of analysis affects their conclusions. Architectural capabilities at the corporate level may differ substantially from product-level capabilities (Galunic & Eisenhardt, 2001; Henderson & Clark, 1990). In addition, the complementary roles of architectural and modular capabilities need to be examined, since they jointly affect a firm's innovation capabilities (Sanchez & Mahoney, 1996). Attention to contextual and firm-level differences will be important in untangling their effects. Below are some potential avenues for future research.

Intellectual Property in Modular Systems

To delineate the boundary conditions of our theory, additional work is needed on the role of property rights in sustaining modular and architectural performance advantages. For example, if information about modular design practices is easier for competitors to acquire, firms may patent more aggressively in the presence of modularity, even if patenting results in the release of sensitive information (Rivkin, 2000). Firms have increased their use of patenting in order to force cross-licensing agreements and to block or avoid being blocked from certain technologies, especially in complex products (Cohen, Nelson, & Walsh, 2000).

The use of modular design might facilitate these uses of intellectual property by clarifying the boundaries of a firm's functional solutions. It is important to explore the various tools firms use to consolidate their advantages and how altered intellectual asset flows associated with modularity shift the relative importance of the mechanisms firms employ to capture the value of their intellectual assets (McGaughey, 2002).

Modularity in Different Activities

We have focused our theory development on modularity in design in closed technological systems. It is important that, in future research, scholars consider modularity in design in relation to modularity in production, as well as modularity in use (Baldwin & Clark, 2000). While modularity in design facilitates modular production and use, production and customer needs are often the initial stimuli for modularity in design. Sako and Murray (1999) argue that, in the computer sector, customer pull drove the shift toward modularity, while in the auto sector, production-related issues such as flexibility and labor benefits were important drivers (see also Takeishi & Fujimoto, 2001).

A focus on modularity in design ultimately centers on functional performance outcomes (Gershenson et al., 2003). Expanding the theoretical framework to consider production expands that scope because an added dimension, structural cohesiveness—the ability to handle the component as one unit—is also important (Takeishi & Fujimoto, 2001). This paper also highlights a critical boundary condition for research on modularity—the difference between open and closed technological systems. Let us turn to the implications of that boundary condition.

Open Versus Closed Technology Systems

We have explored the benefits of modular design in closed systems in which component interface standards are proprietary. In much of the literature, scholars have investigated modularity in open systems, where component interfaces are standardized across companies (Schilling & Steensma, 2001; Takeishi & Fujimoto, 2001). In open systems, such as personal computers, bicycles, and stereo equipment, firms that outsource components can switch easily among suppliers, and customers who wish to assemble a product on their own can purchase components from different companies (Langlois & Robertson, 1992; Schilling, 2000).

Variation in the use of modular design among open systems component suppliers would enable some of them to gain the innovation benefits described in Propositions 3 through 5. However, rivalry may be more intense, and performance advantages less persistent, as common standards reduce entry barriers (Baldwin & Clark, 1997a,b; Langlois & Robertson, 1992). Hence, architectural capabilities may become relatively more important in open systems. In markets where customers assemble their own products, such as stereos, the locus of sustainable advantage may shift from individual product positions to product platforms or families and the architectural capabilities needed to configure and develop them (Meyer & Lehnerd, 1997; Sanderson & Uzumeri, 1995). In markets where firms assemble the end product, such as bicycles, persistent advantage may reside in the ability to coordinate and integrate design capabilities that reside within loosely coupled networks of suppliers (Baldwin & Clark, 1997b; Fine, 1998).

Modularity may impact opportunities for value creation, along industry value chains and at the business and corporate level, differently in open and closed systems (Galunic & Eisenhardt, 2001; Langlois & Robertson, 1992). However, the definition of open and closed systems must be distinguished from modularity, per se, in order to encourage these comparisons. Fujimoto (2000) argues that the extensive research examining modularity as it affects cross-firm task distribution stems from an equating of closed and open systems with integral and modular architectures. Modular designs and design practices often coincide with open systems. However, Fujimoto points out that they are also prevalent with closed systems, where firms retain control over both the interface specifications (visible design rules) and the modules (hidden information). Examples include mainframe computers and machine tools. In the case of closed architectures, it is still possible to have what Takeishi and Fujimoto (2001) term *modularization in interfirm systems*. Brusoni and Prencipe (2001), for example, describe organizational "coordinators" that manage a series of collaborative arrangements with suppliers to create closed architecture aircraft engines.

Products traditionally designed with functionally and structurally interdependent parts, such as automobiles and portable consumer electronics, may shift in the direction of modularity, without necessarily resulting in open systems or more outsourcing. In the case of the automotive sector, for example, Takeishi and Fujimoto (2001) surveyed 153 first-tier suppliers and found no evidence that modularity was resulting in shifts toward an open system. Furthermore, firms in closed industries shifting toward outsourced modules feel it is critical to maintain some design knowledge of the modular content inhouse, to integrate the outsourced modules into the remainder of the product (Takeishi, 2002). The choices firms make on this front are particularly intriguing, since they shed light on the efficiency with which organizations can collaborate on design, development, and production (Langlois, 2002).

Modularity and the Task and Knowledge Boundaries of the Firm

A reported advantage of hierarchies is their ability to combine and transfer certain types of knowledge more efficiently than the market can (Kogut & Zander, 1992). Tacit knowledge, such as that required to integrate elements of complex products, can be particularly difficult to communicate (Hansen, 1999). By reducing the tacitness of architectural knowledge, modular design practices enable separate organizations to coordinate activities that would otherwise be carried out within the firm (Garud & Kumaraswamy, 1995).

However, as Brusoni and Prencipe (2001) note, efficient task boundaries may differ from the knowledge boundaries that sustain a firm. In particular, firms require a much broader knowledge base to manage development across organizational boundaries than is needed for their own development activities (Takeishi, 2002). To elaborate modularity's implications for a theory of the firm, it would be useful to examine the drivers of and relationships between these two borders. The influence of modularity on agency is likely to be an important factor shaping outsourcing arrangements and the task borders of the firm. As we discussed, modularity creates clearer links between design effort and outcomes. The accountability dimension of modularity is one of the factors that facilitate outsourcing. Given the pervasive role of agency relationships within and across organizations (Eisenhardt, 1989; Sharma, 1997), the information benefits of modular approaches, with respect to reducing agency in establishment of firms' task boundaries, as well as intrafirm management of agency, provide a valuable direction for future inquiry.

While agency may influence firm task boundaries, it is less clear what drives a firm's knowledge boundaries. Modular design clarifies the functional domain (e.g., superior graphics or sound fidelity) of a firm's capabilities and allows for the evolution of scientific and technological competencies that support those functions. However, the ability to assimilate new technologies is also constrained by the current product architecture. Hence, product functionality and past technologies shape the trajectory along which a firm accumulates new knowledge. Firms that configure design and development tasks so as to foster an efficient balance between the exploitation of existing knowledge and the extension/renewal of this knowledge through exploration ought to have an advantage. Knowledge flows across organizational boundaries can be instrumental in maintaining such a balance, which suggests a complementary relationship between a firm's task and knowledge boundaries. Further investigation along these lines might push the knowledge-based theory of competitive advantage closer to becoming a knowledge-based theory of the firm (Eisenhardt & Martin, 2000).

How Much Modularity Is Good for Innovation?

In our theoretical framework we proposed that modular design accelerates incremental innovation, increases the reliability of a firm's design changes, and facilitates radical component innovation. However, these advantages must be balanced against the potential costs of modularity. Limiting interdependence between components too extensively eliminates opportunities to improve performance and may reduce the usefulness of a firm's innovations (Ethiraj & Levinthal, 2004; Fleming & Sorenson, 2001). In open systems, modularity may also hinder innovation by component suppliers by prohibiting architectural change (Galvin & Morkel, 2001).

Research that examines tradeoffs between the kinds of innovation modularity fosters and deters, as well as between the size and durability of performance advantages (e.g., see Rivkin, 2000), would be especially instructive. The relationships between architectural and component innovation, and modularity's impact on them, also need to be better understood. Architectural innovation involves remapping functions to components, and changes to architectural parameters may stimulate radical component innovation.[3] Although architectural innovation is less frequent in modular products, if firms acquire deeper and broader system-level knowledge by applying modular design principles, they may perform better when architectures evolve (Sanchez & Mahoney, 1996).

Exploring how much modularity is "enough" also opens the question of industry influences on levels of modularity, the importance of initial design choices, environmental contingencies such as volatility, and causal relationships to value-chain architecture. Empirically exploring the link between modularity and the durability of exceptional performance advantages provides a useful starting point for examining the broader implications of modularity for dynamic capabilities, task versus knowledge boundaries, organizational strategy, industry dynamics, and market structure.

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[3] For example, the move from 8" to 5.25" disk drives initiated a search for components better suited to the smaller architecture. Seagate Technology replaced the transmission system, which was based on a fan belt, pulley, and AC motor, with a pancake motor, which eliminated the need for the pulley and fan belt (Christensen et al., 1998).

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